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Laser cutting of different polymeric plastics (PE, PP and PC) by a CO_2 laser beam☆

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Abstract

This work investigates the application of the CO_2 laser cutting process to three thermoplastic polymers, polyethylene (PE), polypropylene (PP), polycarbonate (PC) in different thicknesses ranging from 2 to 10 mm. The process parameters examined were: laser power, range of cutting speed, type of focusing lens, pressure and flow of the covering gas, thickness of the samples. Furthermore, the values of kerf widths on top (L_{sup}) and bottom (L_{inf}) thicknesses, the melted transverse area, the melted volume per unit time and surface roughness values (R_a) on cut edges were also measured.

Keywords: Thermoplastic polymers; CO_2 laser cutting process; Kerf widths

1. Introduction

The cost of laser technology is still extremely high, though it is constantly falling, and consequently its use is justified only if the quality of the end product is decisively better and if the process becomes more reliable. Laser applications in plastic materials cutting have grown considerably in many industries since it is now possible to achieve a superior quality finished product along with greater process reliability. The aim of this study is to investigate analytically and systematically the cutting process of plastic materials, specifically CO_2 laser cutting applied to polyethylene, polypropylene and polycarbonate, in order to provide potential, future industrial users of this technology with exhaustive information on optimum power levels and cutting speeds as well as quality of the cut edge. This paper presents the results of an experimental investigation centred on the influence that the main parameters, sample thickness, laser power, cutting speed, type, pressure and flow rate of the covering gas have on overall process efficiency. Surface roughness measurements were also taken.

2. Different laser cutting techniques

Generally speaking, a very large number of organic materials present a high surface absorption for the wavelength (10.6 μm) typical of CO_2 laser whereas they are transparent at the 1.6 μm wavelength of a Nd:YAG laser [1–4]. Consequently, a CO_2 laser with a power as low as 500 W may be sufficient to cut materials such as glass, plastic, ceramics, rubber, paper, cardboard, fabrics, wood, leather [1,4,5]. All polymers can be cut by means of a combination of three processes: fusion, vaporization and chemical degradation [1,2]. It is possible to classify plastic materials according to which of these three processes prevails when they are cut.

2.1. Fusion cutting

The majority of thermoplastic polymers are cut by fusion of the material [6–9]. The mechanism underlying this phenomenon is similar to that of metal cutting with inert gases, since the laser beam produces fusion while the covering gas removes the molten material, thus generating the actual severing of the piece. In the case of polymers, the gas used is compressed air. Kerf widths range from 0.2 to 0.8 mm, and vary according to the thickness of the material. The cut edge and faces are macroscopically smooth with some streaks—which are produced by the melted material—that run from the laser-beam entry point to its exit point. The

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materials that are cut by fusion include PE, PP and PC [1,2].

2.2. Vaporization cutting

One of the most commonly used polymers that is generally cut by laser through vaporization is PMMC (Plexiglass). The quality of the resulting cut is excellent. If the cut edges of the finished product are to acquire a glossy finish, the pressure and flow of the cutting gas (compressed air) must be adequately low so as to make it possible for the residual molten material still present on the cut faces and edges to solidify in a nonturbulent manner [1,2].

2.3. Cutting through chemical degradation

The cutting of polymers through chemical degradation (when this is chosen as prevailing removal process) tends to produce smoke with carbonaceous particles which often results in a residue being deposited on the cut edges and faces [1,6,7]. Chemical degradation is used to cut thermosetting materials. The process requires the use of a higher power level as compared to simple fusion cutting because a three-dimensional lattice needs to be broken and not merely a linear chain of monomers as in the case of thermoplastics [6–10]. Therefore, it should come as no surprise that:

- cutting speeds are generally lower for thermosetting materials as compared to thermoplastics;
- at the point of interaction between laser and material, the resulting surface temperatures are higher (≈3000 °C versus ≈1000 °C for thermoplastics) [1,2].

The cut edges and faces are usually flat and smooth since they are the result of a removal process that does not employ molten material. The cut surface may be covered by a thin but extensive layer of carbonaceous dust (similar to carbon black) which can be removed with a dust cloth (even though usually some dark residues are ultimately still visible). As for other polymers, typical kerf widths range from 0.2 to 0.8 mm and the profile of cut edges is approximately perpendicular to the surface of the sample [1,2].

3. Experimental analysis

A ROFIN SINAR fast axial flow CO$_2$ laser, with a maximum 1.5 kW power, was used to process three different thermoplastics:

- 2, 3, 4, 5, 6, 7, 8 and 10 mm thick sheets of high density polyethylene (HDPE). The 6, 7, 8 and 10 mm thick sheets were obtained by placing two 2, 3, 4 and 5 mm thick sheets one on top of the other.
- 2, 3, 4, 5, 6, 7, 8 and 10 mm thick sheets of isotactic polypropylene (PP). The thicker sheets, i.e. the 6, 7, 8 and 10 mm thick ones were obtained by placing two 2, 3, 4 and 5 mm thick sheets one on top of the other.
- 3, 4 and 5 mm thick sheets of compact, extruded, polycarbonate (PC), reinforced with PC8030 type strengtheners. In this case we did not investigate thicker sheets made of two layers because of the poor quality of the cut of the contact surfaces. The poor quality was due to the fact that the molten material and its vapors, discharged from the cutting channel, wedged themselves in between the contact surfaces of the two materials placed one on top of the other.

Table 1
Main mechanical and thermal properties of PE, PP and PC laminates

Properties	HDPE	PP	PC
Density (g/cm^3)	0.95	0.90–0.91	1.2
Yield strength (MPa)	20	30	62
Ultimate tensile strength (MPa)	25	36	65
Elongation (%)	380	21	90
Coefficient of linear expansion (20–90 °C) (mm/m °C)	0.14–0.20	0.11	0.065
Thermal conductance (20 °C) (W/m K)	0.32–0.43	0.26	0.25

In Table 1 below we report the main mechanical and thermal properties of the materials used in our experiment [7–9].

The ultimate aim of the investigation conducted on laser cutting was to determine critical speeds V_c (i.e. the maximum speed at which the cut passes right through the entire thickness of the material). This parameter proved to be influenced by the following variables: nozzle, distance between nozzle and sample, lens, thickness, laser power, cutting speed, pressure and flow of the covering gas. In consideration of the numerous parameters that influence cutting process, cut edge quality and operating speeds, we decided to keep three parameters constant: focussing lens, nozzle and nozzle–sample distance. In the nozzle employed for cutting plastics, the gas jet orifice has a 0.8 mm diameter. Its function is to discharge gas coaxially to the laser beam. The extremely small size of the orifice ensures a thin, punctiform and efficacious jet of gas that makes it possible to obtain the narrowest possible kerf width and, simultaneously, high operating speed thanks to the rapid removal of the molten material. The nozzle–sample distance was fixed at 1 mm, because at this distance it is possible to obtain an optimum gas jet convergence and pressure in the cutting channel. The lens employed was a ZnSe type lens with a 5″ focal length, a positive meniscus lens, which makes it possible to focus the beam in a small-sized focal spot (diameter 200–300 μm) in respect to power and diameter of the incident laser beam. Power level was kept within the range from 200 to 1400 W; this range enables the detection of critical speed. We then tested different speeds ranging from 0.25 to 10 m/min at various pre-established power levels. In order to determine the types of gas and relevant pressures that would be the best suited for our experimentation, we carried out specific preliminary trials on 5 mm thick PE.

The gases we thus decided to use were: nitrogen (N_2), argon (Ar), compressed air (CA). A comparison of the different gases, employed at a constant pressure of 3 bar, indicated no appreciable variations in the quality of the cut edges or the value of critical speed, except when cutting was carrying out at the lowest power setting, i.e. 200 W. In this case, when using nitrogen the cutting process was carried out at a critical speed lower than the speed recorded with the other two gases (N_2 = 0.6 m/min; Ar = 0.7 m/min; CA = 0.75 m/min). Since the increase in speed is almost negligible we chose CA as our working gas because it is the less expensive of the three gases tested. As far as gas pressure is concerned, we tested the interval ranging from 2 to 5 bar in order to assess the influence of this parameter on the quality of the cut edge and kerf width. This experiment was conducted with a constant power level (1000 W) and at a constant speed (2.5 m/min). It was found that at higher pressures the amount of molten material fin present on the bottom cut edge is lower. Consequently, we chose a 3 bar pressure for all the experimentation, which is an optimum value since a comparison with the results of experiments conducted at 4 and 5 bar did not highlight an appreciably higher quality of cut surfaces.

4. Results and discussion

Tables 2–4 report—in the form of numerical values—the most significant results obtained from the laser-beam cutting of thermoplastic polymers PP, PE, and PC. It is evident

Table 2
Polypropylene

Test no.	Thickness (mm)	Power (W)	Cutting speed (m/min)	L_{sup} (μm)	L_{inf} (μm)	ΔL ($L_{\text{sup}} - L_{\text{inf}}$) (μm)	Melted area ($10^{-3}\,\text{mm}^2$)	Melted volume/s (mm^3/s)
1L	3	200	2.3	326	277	49	904	35
2L	3	300	3.3	387	346	41	1099	60
3L	3	400	4.1	425	365	60	1185	81
4L	3	500	5.1	460	275	185	1102	94
5L	3	600	6.0	462	266	196	1092	109
6L	3	800	7.8	427	556	−129	1475	192
7L	3	1000	9.0	491	581	−90	1608	241
35L	5	200	1.1	330	416	−86	1865	34
36L	5	300	1.6	355	391	−36	1865	50
37L	5	400	2.0	385	469	−84	2135	71
38L	5	500	2.4	392	503	−111	2237	90
39L	5	600	2.9	442	390	52	2080	101
40L	5	800	3.7	510	467	43	2482	151
41L	5	1000	4.5	491	393	98	2210	166
42L	5	1200	5.3	534	421	113	2388	211
43L	5	1400	6.1	515	430	85	2362	240

Table 3
Polyethylene

Test no.	Thickness (mm)	Power (W)	Cutting speed (m/min)	L_{sup} (μm)	L_{inf} (μm)	ΔL ($L_{\text{sup}} - L_{\text{inf}}$) (μm)	Melted area ($10^{-3}\,\text{mm}^2$)	Melted volume/s (mm^3/s)
8L	3	200	1.03	430	441	−11	1306	28
9L	3	300	1.08	369	531	−162	1039	31
10L	3	400	2.03	582	536	46	1677	64
11L	3	400	2.02	503	588	−85	1636	60
14L	3	600	3.02	590	540	50	1695	90
15L	3	800	4.01	622	844	−222	2199	150
16L	3	1000	5.01	797	786	11	2374	209
17L	3	1200	6.00	753	1100	−347	2780	278
18L	3	1400	6.08	860	793	67	2480	281
44L	5	200	0.05	298	836	−538	2835	24
45L	5	300	0.07	346	1070	−724	3540	41
46L	5	400	0.09	319	1027	−708	3365	50
48L	5	600	1.03	392	1100	−708	3730	81
49L	5	800	1.09	374	969	−595	3357	106
50L	5	1000	2.03	386	951	−565	3342	128
51L	5	1200	2.07	440	949	−509	3472	156
52L	5	1400	3.02	408	901	−493	3272	175

Table 4
Polycarbonate

Test no.	Thickness (mm)	Power (W)	Cutting speed (m/min)	L_{sup} (μm)	L_{inf} (μm)	ΔL ($L_{\text{sup}} - L_{\text{inf}}$) (μm)	Melted area (10^{-3} mm^2)	Melted volume/s (mm^3/s)
19L	3	200	3.4	297	117	180	712	40
20L	3	300	4.7	325	162	163	730	57
21L	3	400	5.8	311	218	93	793	77
22L	3	500	7.2	335	211	124	819	98
25L	3	600	8.3	331	300	31	946	131
26L	5	200	1.6	377	273	104	1625	43
27L	5	300	2.3	330	257	73	1467	56
28L	5	400	2.8	361	296	65	1642	77
29L	5	500	3.4	323	322	1	1612	91
30L	5	600	4.0	335	280	55	1537	103
31L	5	800	5.1	366	293	73	1647	140
32L	5	1000	6.2	348	237	111	1462	151
33L	5	1200	7.2	346	355	−9	1752	210
34L	5	1400	8.3	375	497	−122	2180	302

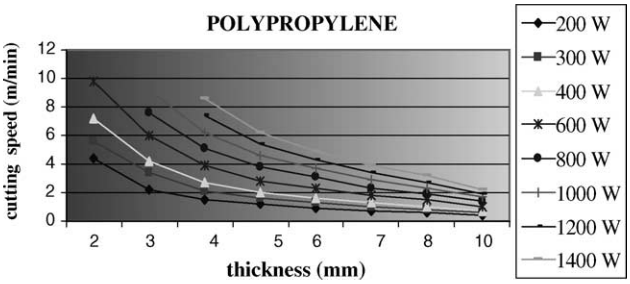

Fig. 1. Cutting speed vs. thickness for different laser power levels for PP sheets.

from these tables that numerical values are given only for the findings related to 3 and 5 mm thick sheets whereas for all other thicknesses included in the adopted range, i.e. 2–10 mm, only a graphic presentation of the results is given.

We report with graphs the data concerning the curve of critical cutting speed versus thickness, at a constant laser power for PP and PE (see Figs. 1 and 2). This hyperbolic trend, which is in line with the results that have always been found in respect of cutting of ferrous and nonferrous materials [2,11–13], was verified at different power levels (200–1400 W), thus creating a family of hyperbolae, both for PP and PE. Similarly, we studied the variation of the parameter critical speed versus laser power, at a constant thickness. Fig. 3 shows, for a thickness of 5 mm, the typical rectilinear trend, with constant slope for PE, PP, PC, which is similar to the one obtained with metals in general [2,11,13].

The graphs of Figs. 1–3 and Tables 2–4 are of the utmost importance in order to predetermine, theoretically, the real possibilities of a CO_2 laser system, of a given laser power, in cutting the three polymers PE, PP, PC and the related thicknesses. They are also useful in predetermining which workbench can better meet the effective requirements of the industrial end-user for workpiece movement or laser-beam movement, and is better suited to the technological-manufacturing process.

Figs. 4–6 show photomacrographies illustrating the appearance of the top and bottom cut surfaces of 3 and 5 mm thick sheets, and the appearance and geometry of two cross-sections of cut materials of the same thicknesses. Since it is difficult to obtain cuts of plane-parallel faces, that is, cuts with kerf width on the bottom ≈ kerf width on the top, one of the aims of this work was to investigate in an exhaustive manner the way in which these two parameters vary versus the laser power employed, at a constant thickness (3 or 5 mm), and at discrete variations of cutting speed values, as shown in Tables 2–4. Given that kerf width on the bottom, kerf width on the top and ΔL evidently vary as a function of thickness, laser power, cutting speed

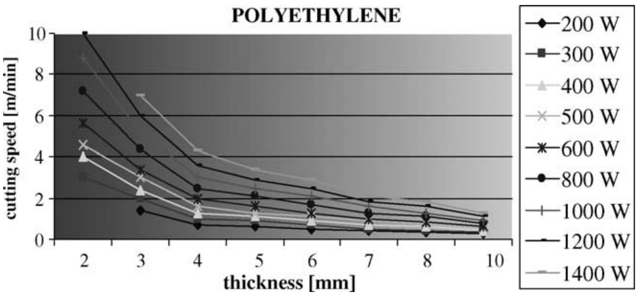

Fig. 2. Cutting speed vs. thickness for different laser power levels for PE sheets.

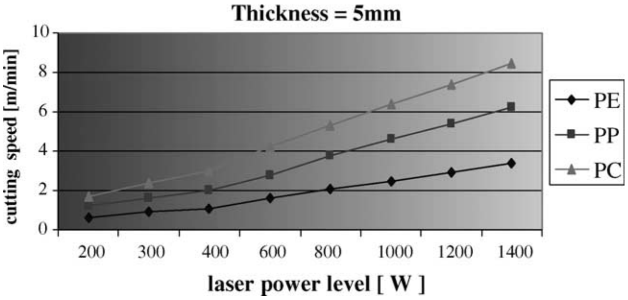

Fig. 3. Cutting speed vs. laser power level for 5 mm thick sheets of PE, PP and PC.

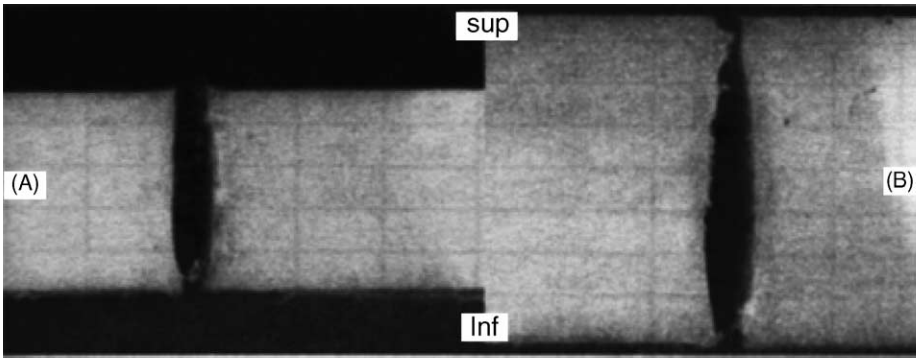

Fig. 4. Macrographs on cross-sections of PP sheets laser cuts (sup is the kerf width on the top and inf is the kerf width on the bottom).

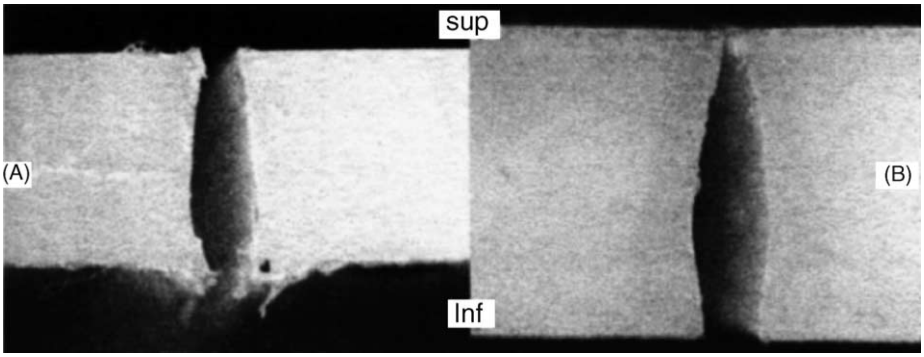

Fig. 5. Macrographs on cross-sections of PE sheets laser cuts.

as well as type of polymer involved (PE, PP and PC), the importance of these curves even during the design of the finished product, particularly if its geometry is somewhat complex, is obvious.

It is evident that if we choose an extremely low numerical value (≈0) for ΔL it means that we wish to obtain cuts that are as close as possible to plane-parallel surfaces; conversely, ΔL with high numerical values entail kerf width on the bottom ≠ kerf width on the top and a geometric profile which can be V-shaped (an upright V or an upside-down V) or “barrel-shaped”. Using 3 and 5 mm thick sheets we investigated the shape of the melted surface, i.e. the transverse area in respect of the length of the cut, and the relevant melted volume per unit time. The latter parameter was obtained quite simply as the product of the melted surface times the critical speed of the cutting process (in mm/s). These results are shown in Tables 2–4. An analysis of the tables and graphs can give an accurate, quantitative idea of how the geometry and the profile evolve. With a certain degree of approximation, it can even provide some sort of tool for assessing cutting process efficiency for all the materials and thicknesses tested. Let us take for example a typical thickness that is widely used in manufacturing processes, i.e. 3 mm thick PP. If we look at Table 3 we can see that:

- Test 1L which uses the lowest laser power (200 W) (and which therefore entails lower investment expenditure and operating expenses), has a ΔL of only 49 μm (but not

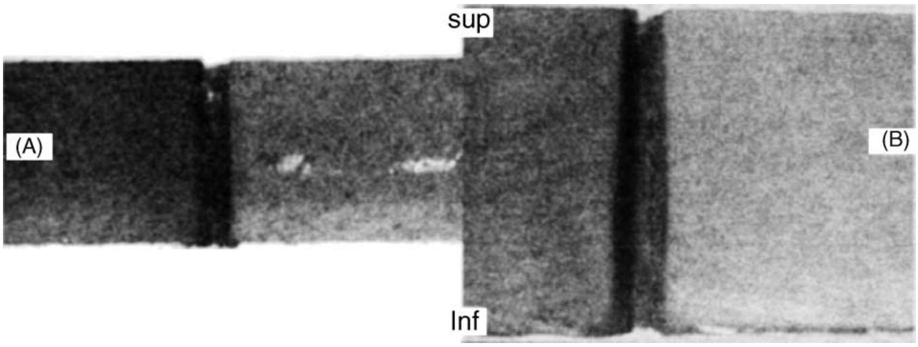

Fig. 6. Macrographs on cross-sections of PC sheets laser cuts.

Table 5
R_a experimental values

Material	Thickness (mm)	Power (W)	V_c (m/min)	R_a (μm)
PE	3	500	2.7	1.07
	5	500	1.1	1.06
PC	3	600	8.2	2.02
	5	1200	7.2	2.08
PP	3	1000	9	0.67
	5	1200	5.3	1.4
Fe 370	5	1000	1.9	5.24

the lowest), cut edges which are almost plane-parallel, a minimal molten volume (35 mm^3/s) but an insignificant cutting speed, a minimum of only 2.3 m/min.

- Test 7L, also involves almost plane-parallel faces, but with a larger ΔL (90 μm versus 49 μm of the previous test) and a high melted volume (seven times higher than the previous one, 241 mm^3/s versus 35 mm^3/s). Cutting speed can be as high as 9 m/min, which is well above the 2.3 m/min cutting speed of test 1L. In this case a much more powerful laser source is needed, 1000 W versus 200 W of the previous test and this entails a considerable increase in initial investment expenditure and in operating expenses (system cost per hour), in other words, higher depreciation expense and a higher incidence on the cost per linear meter of finished product.
- If a cutting speed of 2.3 m/min does not meet the end-user's manufacturing requirements, one could consider the values of kerf width on the bottom and kerf width on the top, ΔL and molten volume of tests 2L and 3L which make it possible to obtain a cutting speed of 3.3 or 4.1 m/min with a slight increase of the above mentioned parameters and with minor increases in laser power (300 or 400 W) (the graph of power versus speed is still a straight line).

To conclude, we found that not always higher cutting speeds are indicative of greater process efficiency.

4.1. Surface roughness measurements

We took surface roughness (R_a) measurements on the cut edges using a bench roughness tester (a Surtronic 3P type device manufactured by Rank Taylor Hobson). The samples we chose were the same as those used to visualise the cross-sections of the cut. The roughness measurements of thermoplastic laminates were then compared with the roughness measurement of a steel sample (5 mm thick Fe 370 which had been cut by laser beam under optimum experimental conditions). Table 5 reports the numerical values of R_a observed for the three materials, PE, PP and PC (on two thicknesses, i.e. 3 and 5 mm) and, for comparison purposes, the same value recorded for 5 mm thick Fe 370 construction steel. We can see that:

- for PE, the variations in thickness and speed do not entail notable variations in R_a (≈1 μm);
- for PP, if we double the thickness, keep power almost constant, and almost halve the speed, the value of R_a doubles, rising from ≈0.7 to 1.4 μm;
- for PC, if we double both thickness and power, at cutting speeds very close one to the other, the R_a values observed do not differ very much (from 2.02 to 2.08 μm), and fall within the range ≈2–3 μm.

All of the three materials generally follow the rule (which the results of experiments on ferrous and nonferrous metals have already amply validated) according to which the value of R_a diminishes as cutting speed increases. Moreover, they all show R_a values which are much lower if compared, for instance, with a typical construction steel. It follows that for the power range 500–1500 W and for the speed range 1–10 m/min, PE and PP can be said to assume R_a values ≈0.5–1.5 μm, whereas for PC, within the above mentioned ranges, R_a values are ≈2–3 μm.

5. Conclusions

The experimental research conducted has provided ample responses to the doubts and questions that a large number of industrial operators ask themselves when they have to decide which laser cutting technology to adopt for their production cycle. The choice of three thermoplastic polymers such as polyethylene (PE), polypropylene (PP) and polycarbonate (PC) having a thickness ranging from 2 to 10 mm was not a chance decision but rather it was determined by specific manufacturing requirements in terms of process and product. We drew our conclusions after an exhaustive, critical examination of the many different process parameters involved which are closely correlated one with the other and with an eye always on cut edge and faces quality. We parameterized the values of kerf width on the bottom (L_{inf}), kerf width on the top (L_{sup}) as well as ΔL ($L_{\text{sup}} - L_{\text{inf}}$), the melted transverse area and, ultimately, the melted volume per unit time (mm^3/s). It was found that there are optimum values that apply to the above mentioned parameters and that not always high cutting speeds are synonymous with good process efficiency. For all of the three polymers used, cutting speeds proved to be of great interest and much higher than those found in the literature in respect of ferrous and nonferrous metals. The vast range of laser power settings (200–1400 W) used in our research leads us to conclude that in many cases the employment of powerful CO_2 laser sources is not necessary; at times just a few hundred Watts may be all that is required.

The measurements of roughness (R_a) taken on cut surfaces (for PP, PE, PC) highlighted very low values (0.5–2 μm) if compared with those observed on similar thicknesses of a typical construction steel, such as laser cut 5 mm thick Fe 370 ($R_a \approx 5$ μm). For all three polymers, laser cutting took place by means of a predetermined, localized fusion process followed by a rapid removal of the molten material thanks to a gas jet towards the bottom. Generally, this process makes it possible to avoid the formation of fin (or the formation of only a very small quantity of fin). Another finding is that the quality of cut edges and faces is much better in the case of PP rather than in that of PE. We also observed that micro-droplets of re-solidified molten material persist on cut surfaces of PC. In the light of the above, and bearing in mind all the parameters as well as the quality of the cut achieved, we can conclude that were we to specify the "degree" of laser cutting workability of the three polymers under investigation, we would rank them as follows: PC high, PP medium-high, and PE lower (even though the latter cuts well and easily).

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